MÄLARDALEN UNIVERSITY
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FULL-SCALE FIRE EXPERIMENTS WITH MINING VEHICLES IN AN UNDERGROUND MINE

Rickard Hansen & Haukur Ingason

RESEARCH REPORT 2013:2
STUDIES IN SUSTAINABLE TECHNOLOGY

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Preface

This report is part of the research project "Fire spread and heat release rate of underground mining and tunnelling vehicles – BARBARA", conducted by a research group at Mälardalen University.

The project is aimed at improving fire safety in mines and tunnels during construction in order to obtain a safer working environment for the people working for the mining companies, as well as the tunnelling companies in Sweden or for visitors in mines open to the public. The following organisations are participating in the project: Mälardalen University, LKAB, Atlas Copco Rock Drills AB, Björka Mineral AB, Skanska Sverige AB and Svensk Kärnbränslehantering AB. The project has been funded by KK Stiftelsen (the Swedish Knowledge Foundation).

Västerås in June 2013.
Rickard Hansen & Haukur Ingason

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The project was sponsored by KK-stiftelsen (the Swedish Knowledge Foundation), LKAB Mining Corporation, Atlas Copco Rock Drills AB and Björka Mineral AB.

Abstract

This report is part of the research project "Fire spread and heat release rate of underground mining and tunnelling vehicles – BARBARA", conducted by a research group at Mälardalen University. The project is aimed at improving fire safety in mines and tunnels during construction in order to obtain a safer working environment for the people working for the mining companies, as well as the tunnelling companies in Sweden or for visitors in mines open to the public.

This report comprises two full scale fire experiments in a mine drift at Björka Mineral in Sala, Sweden, involving a loader and a drilling rig respectively.

The main purposes of the report are:

- Obtain data which can validate models to calculate the total heat release rate of mining vehicles.
- To produce total heat release rate curves for representative mining vehicles.

This report describes the determination of the heat release rate at fire experiments, the involved mining vehicles, the site of the fire experiments, the experimental setup and finally the results from the experiments. The results are thereafter discussed and finally conclusions are drawn.

It was found in the experiment involving the wheel loader that the front part of the vehicle (front tyres etc.) never ignited. The maximum measured heat fluxes at the front tyres were found to never exceed the critical heat flux of natural rubber and thus ignition never occurred. Furthermore, the maximum temperature recorded at the hydraulic hoses in the waist was 381 K and thus the low temperatures did not allow for further fire spread. The maximum heat release rate from the experiment was 15.9 MW and it was attained approximately 11 minutes after ignition. The resulting heat release rate curve of the wheel loader fire displays a fire that is dominated by initially the sudden increase when primarily the first tyre is engulfed by flames and then by the slowly declining heat release rates of the large tyres of the vehicle. Still, the stop of fire spread from the waist and forward clearly shortened the duration of the fire considerably.

It was found in the experiment with the drilling rig that the entire vehicle had participated in the fire and the combustible material had been consumed – except for the hydraulic hoses approximately two meters in front of the cab and forward, some amount of hydraulic oil and a major part of the low voltage cable on the cable reel. The maximum temperatures of the

measuring points along the boom all exceeded 1300 K, it is unclear why ignition did not take place in the front parts of the hydraulic hose. The maximum heat release rate from the experiment was 29.4 MW and it was attained after 21 minutes. The resulting heat release rate curve of the drilling rig displays a fire with high heat release rates and relatively short lived – compared with the fire in the wheel loader. Practically all the combustible items were ignited in the early phases of the fire.

Further validation work should take place with respect to validating the experimental data with output data from theoretical models.

1 Introduction

Research regarding fire safety in mines has so far mainly been directed towards coal mines. Thus the need for additional knowledge, recommendations, models, engineering tools etc for hard rock underground mines are in great need.

This aim of the current research project "Fire spread and heat release rate of underground mining and tunnelling vehicles – BARBARA" is to improve fire safety in mines and tunnels during construction in order to obtain a safer working environment for the people working for the mining companies, as well as the tunnelling companies in Sweden or for visitors in mines open to the public.

The research project continues where the research project GRUVAN ended and focuses on the issue of vehicles in underground structures. The project consists of different steps, where each step is based on results and knowledge from the earlier steps. The steps are: literature survey, investigation regarding fire causes and fire behaviour during vehicle fires in underground mines (research involving incident reports), small-scale fire experiments involving equipment details from vehicles found in underground structures, and finally full-scale fire experiments in a mine involving mining and tunnelling vehicles.

This report comprises two full scale fire experiments involving a wheel loader and a drilling rig respectively in a mine drift at Björka Mineral in Sala, Sweden.

The main purposes of the report are:

- Obtain data which can validate models to calculate the total heat release rate of mining vehicles.
- To produce total heat release rate curves for representative mining vehicles.

The output of the project will mainly consist of:

- Measured values from the full-scale tests. Few full-scale tests have been performed and the measures values are important in order to be able to use the model for creation of design fires for underground structures.
- The developed model in the GRUVAN project can be validated and the results will also be of use to future projects.
- The findings in the field of ignition and fire spread will be of value for manufacturers designing new vehicles and machines and for fire prevention in new as well as existing vehicles.

- The results regarding fire spread, heat release rate and smoke production will be useful in the work with fire safety during construction of tunnels and in the mining industry. These results will also be of great importance for the fire- and rescue services in their incident planning.

2 Background

Several new mines are nowadays opened to meet the increasing worldwide demand on mineral resources. More tunnels and underground constructions are also built as the cities grow and valuable land is used for other building purposes. Tunnels are used to shorten distances and underground constructions are built for many different reasons. Only in Sweden almost 200 kilometers of tunnels are under planning or construction.

The Nordic bedrock has shown satisfactory qualities for terminal storage of nuclear waste and safe underground constructions for waste disposal are planned or under construction in both Finland and Sweden. The same fleets of vehicles that are used under construction of tunnels are used in the mining industry.

Information about relevant risks, fire spread in vehicles and machines and the heat release rates for different types of fires is the base in both the preventive work as well as the incident planning. Few full-scale tests have been performed and the information needed to validate calculations and estimations cannot fully be provided. The knowledge would be valuable for companies manufacturing underground vehicles, as well as for the construction or mining companies and first responders.

As there is a great need for full-scale fire experiments involving mining vehicles, it was decided to carry out full-scale tests involving a wheel loader and a drilling rig respectively.

3 Full-scale fire experiments

In May 2011 two full-scale fire experiments on mining vehicles were conducted in an underground mine at Björka Mineral in Sala, Sweden. The experiments involved a wheel loader and a drilling rig respectively and were conducted in order to provide much needed data for future fire safety designs in underground mines. Below, the vehicles, experiments etc. are described.

3.1 The determination of the heat release rate during the fire experiments

The heat release rate in the fire experiments was determined through oxygen calorimetry, i.e. by measuring the mass flow rate, gas concentrations and temperatures at certain heights at the far end of the mine drift – downstream of the fire source – where the fire experiments were conducted.

The method relies heavily on installed thermocouples at every measuring point – which are inexpensive and relatively easy to install – in order to reduce the dependence upon the very expensive and sensitive gas analysis instruments.

Assuming that the local gas temperature and the local gas concentration correlate through the average values over the cross-section [1], the heat release rate can be calculated using the following expression:

$$\dot{Q} = \frac{13100 \cdot \rho_0 \cdot u_0 \cdot A \cdot \left(\frac{M_{O_2}}{M_a}\right) \cdot \left(1 - X_{H_2O,0}\right)}{\frac{0.1}{X_{O_2,0}} + \frac{1 - X_{O_2,avg} \cdot \left(\frac{X_{O_2,avg}}{1 - X_{CO_2,avg}}\right)}{X_{O_2,0} - \left(X_{O_2,avg} \cdot \left(\frac{1 - X_{CO_2,0}}{1 - X_{CO_2,avg}}\right)\right)}} \quad \text{[kW]} \qquad (1)$$

Where

ρ_0 is the ambient air density [kg/m³]

u_0 is the cold gas velocity in a mine drift [m/s]

A is the cross-sectional area [m²]

M_{O_2} is the molecular weight of oxygen, which was set to 32 g/mol

M_a is the molecular weight of air, which was set to 28.95 g/mol

$X_{H_2O,0}$ is the mole fraction of water in the ambient air, which was set to 0.005

$X_{O_2,avg}$ is the average concentration of oxygen

$X_{CO_2,avg}$ is the average concentration of carbon dioxide

$X_{O_2,0}$ is the mole fraction of oxygen in the ambient air, which was set to 0.2095

$X_{CO_2,0}$ is the mole fraction of carbon dioxide in the ambient air, which was set to 0.00033

The above correlation is based upon the work of Newman [2].

The cold gas velocity – u_0 – in equation (1) is expressed as:

$$u_0 = u_{avg} \cdot \left(\frac{T_0}{T_{avg}} \right) \quad \text{[m/s]} \qquad (2)$$

Where

u_{avg} is the average longitudinal velocity in a mine drift [m/s]

T_0 is the ambient temperature [K]

T_{avg} is the average temperature in a mine drift [K]

The average concentrations of oxygen, carbon dioxide and carbon monoxide are calculated using the following equations:

$$X_{O_2,avg} = X_{O_2,0} - \frac{\left(X_{O_2,0} - X_{O_2,h}\right)}{\left(T_h - T_0\right)} \frac{\sum_{i=1}^{N_T}\left(T_i - T_0\right)}{N_T} \quad \text{[mol/mol]} \quad (3)$$

$$X_{CO_2,avg} = X_{CO_2,0} - \frac{\left(X_{CO_2,0} - X_{CO_2,h}\right)}{\left(T_h - T_0\right)} \frac{\sum_{i=1}^{N_T}\left(T_i - T_0\right)}{N_T} \quad \text{[mol/mol]} \quad (4)$$

$$X_{CO,avg} = X_{CO,0} - \frac{\left(X_{CO,0} - X_{CO,h}\right)}{\left(T_h - T_0\right)} \frac{\sum_{i=1}^{N_T}\left(T_i - T_0\right)}{N_T} \quad \text{[mol/mol]} \quad (5)$$

Where

$X_{O_2,h}$ is the oxygen concentration at height h

$X_{CO_2,h}$ is the carbon dioxide concentration at height h

$X_{CO,h}$ is the carbon monoxide concentration at height h

T_i is the temperature at thermocouple i [K]

N_T is number of measuring points with thermocouples

Furthermore, in equation (1) it is assumed that 13 100 kJ/kg is released per kg of oxygen consumed and that air mass flow rate of combustion gases equals the ambient air mass flow rate.

Ingason and Lönnermark [3] used equation (1–3) when determining the heat release rate for a number of large scale tunnel fire tests.

3.2 The determination of the incident radiation heat flux during the fire experiments

The incident radiation heat flux at certain locations was determined using the following equation by Ingason and Wickström [4], developed for the plate thermometer:

$$q''_{inc} = \frac{\varepsilon_{PT} \cdot \sigma \cdot T_{PT}^4 + \left(h_{PT} + K_{cond}\right) \cdot \left(T_{PT} - T_0\right) + \rho_{st} \cdot c_{st} \cdot \delta \cdot \frac{\Delta T_{PT}}{\Delta t}}{\varepsilon_{PT}} \quad \text{[kW/m}^2\text{]} \quad (6)$$

Where:

ε_{PT} is the surface emissivity of the plate thermometer, which was set to 0.8 during the calculations

σ is the Stefan-Boltzmann constant, $5.67 \cdot 10^{-11}$ kW/m$^2 \cdot$K^4

T_{PT} is the temperature of the plate thermometer [K]

h_{PT} is the convective heat transfer coefficient of the plate thermometer [W/m$^2 \cdot$K], which was set to 10 W/m$^2 \cdot$K [4]

K_{cond} is a conduction correction factor [W/m$^2 \cdot$K], which was set to 22 W/m$^2 \cdot$K [5]

T_0 is the ambient temperature [K]

ρ_{st} is the density of steel [kg/m^3], which was set to 8 100 kg/m^3

c_{st} is the specific heat capacity of steel [J/kg·K], which was set to 460 J/kg·K

δ is the thickness of steel plate [m], which was set to 0.0007 m [4]

t is the time [s]

3.3 Mining vehicles used in the fire experiments

Based upon an earlier literature survey performed in the GRUVAN project [6], vehicles are the dominating fire objects in underground mines and the types of vehicles to focus on in future fire studies should be: service vehicles, drilling rigs and wheel loaders. The BARBARA project was given the opportunity to perform full-scale fire experiments on a wheel loader and a drilling rig, both typical for mining applications.

3.3.1 The wheel loader

The wheel loader in question was a Toro 501 DL given to the BARBARA project from LKAB Mining Corporation. It is a diesel driven wheel loader and is used for hauling iron ore.

Table 1. Basic information regarding the Toro 501 DL wheel loader.

Length	10.3 m
Width	2.81 m
Height	2.85 m
Weight	36 000 kg
Tyre dimensions	26,5 x 25 L5S

In table 2 below, an inventory of the combustible components on the wheel loader is found. The effective heat of combustion of the hydraulic hoses, low voltage cable and driver seat was taken as the average value using the results from cone calorimeter tests. The effective heat of combustion of the tyres and the rubber covers was set to 27 MJ/kg [7]. The effective heat of combustion of the diesel fuel was set to 42.6 MJ/kg [8] and 42.85 MJ/kg for the hydraulic oil [9]. When summing up the energy contents of the individual components a total energy content of 76 245 MJ was calculated.

Table 2. Inventory of combustible components found on the Toro 501 DL wheel loader.

Combustible component	Estimated amount	Energy content [MJ]
Tyres (rubber material)	~1 560 kg	42 120
Hydraulic oil	500 liters	16 283
Hydraulic oil in hoses	70 liters	2 280
Hydraulic hoses (rubber material)	~170 kg	4 905
Diesel	280 liters	10 138
Driver seat	~10 kg	228
Electrical cables	~1.5 kg	21
Rubber covers	~10 kg	270

The type of hydraulic oil in the loader was Shell Tellus VG46, with a flashpoint of ~220 °C. No automatic extinguishing system was mounted. Furthermore, the tyres of the wheel loader were filled with water and each tyre contained 577 liters of water. Before the fire experiment, the scoop of the wheel loader was removed.

See figure 1 and appendix A for additional information on the vehicle in question.

Figure 1. **The Toro 501 DL wheel loader used in the full-scale fire experiments in Sala, Sweden**
Photo: Rickard Hansen

3.3.2 The drilling rig

The drilling rig in question was an Atlas Copco Rocket Boomer 322, given to the BARBARA project from Atlas Copco Rock Drills AB. It is an electrically driven drilling rig but is also equipped with a diesel powered engine, which is used when moving from one site to another. In table 3 below some basic information is given.

Table 3. **Basic information regarding the Rocket Boomer 322 drilling rig**

Length with boom	12.4 m
Width	2.19 m
Height	2.95 m
Weight	18 400 kg
Tyre dimensions	13,00 x 20 PR 18

In table 4 below, an inventory of the combustible components is found. The effective heat of combustion of the hydraulic hose was also used for the water hose. The effective heat of combustion of the plastic covers (ABS plastic) was set to 30 MJ/kg [10]. When summing up the energy contents of the individual components, a total energy content of 45 758 MJ was calculated.

Table 4. Inventory of combustible components found on the Rocket Boomer 322 drilling rig

Combustible component	Estimated amount	Energy content [MJ]
Tyres (rubber material)	~155 kg	4 185
Hydraulic oil	350 liters in tank and 150 liters in hoses	16 283
Hydraulic hoses (rubber material)	~390 kg	11 252
Water hose (rubber material)	~40 kg	1 154
Diesel	100 liters	3 621
Driver seat	~10 kg	228
Electrical cables	~450 kg	8 735
Plastic covers	~10 kg	300

The type of hydraulic oil in the drilling rig was the same as for the loader, i.e. Shell Tellus VG46, with a flashpoint of ~220 °C. The rig was equipped with an automatic extinguishing system, using dry powder. It was activated the day before the full-scale fire experiment, thus the containers with dry powder were empty at the time of the fire experiment. No modifications on the drilling rig were made before the experiment. See figure 2 and appendix B for additional information on the vehicle in question.

Figure 2. The Rocket Boomer 322 drilling rig used in the full-scale fire experiment in Sala, Sweden
Photo: Andreas Fransson

3.4 The site of the full-scale fire experiments

The full-scale fire experiments were conducted in the underground facilities of Björka Mineral AB on the outskirts of Sala, where dolomite is mined. Sala is a town in the middle of Sweden, approximately 120 km from Stockholm. The experiments were conducted at level 55, which is a non-active part of the mine. Nonetheless, the infrastructure is still in place with power outlet etc. The preconditions of the potential test site were the following: an active mine with an intact infrastructure, the possibility to steer the smoke in one direction and through one single exhaust, accessibility with vehicles; and the possibility to conduct the fire experiments in a part that would interrupt the normal activities in the mine. All these preconditions were satisfactorily met in the case of the facilities of Björka Mineral AB in Sala. In figure 3 below a plan of the level 55 is seen, pointing out the potential test site within the mine, the closest power outlet etc.

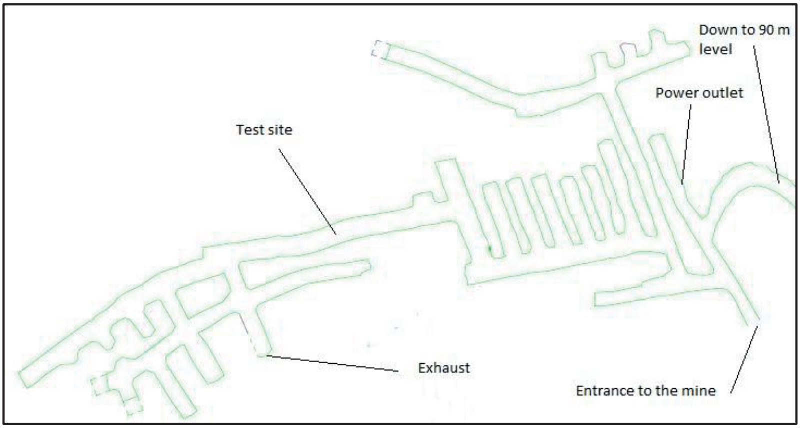

Figure 3. Plan of the level 55

As there was only one exhaust on one side of the test site, all the smoke would be ventilated out through the single exhaust and thus allowing for heat release rate measurements on this side of the test site. The intake of air would be from the entrance of the mine and the lower regions of the mine. Approximate dimensions of the mine drifts in the test area were 6 x 8 meters (H x W).

The mine drift, where the experiments took place, was approximately 100 meters long, approximately 150 meters from the entrance to the mine and 40 meters from the exhaust. There were practically no differences in height between the entrance of the mine and the exhaust. No ventilation fans existed in the immediate area. Parts of the roof in the mine drift were bolted and a PVC-tube for ventilation (not in use) was placed in the roof.

3.5 The experimental setup

In figure 4 below, a schematic plan of the test site and its immediate surroundings is found. The approximate positions of the loader and the drilling rig are shown in figure 4. The assembly point is the position where all personnel were gathered at the time of ignition. The position of the fan is shown in the figure, where also the initial position of the fan during the loader fire experiment is shown (the fan was moved to the other position at the beginning of the fire experiment).

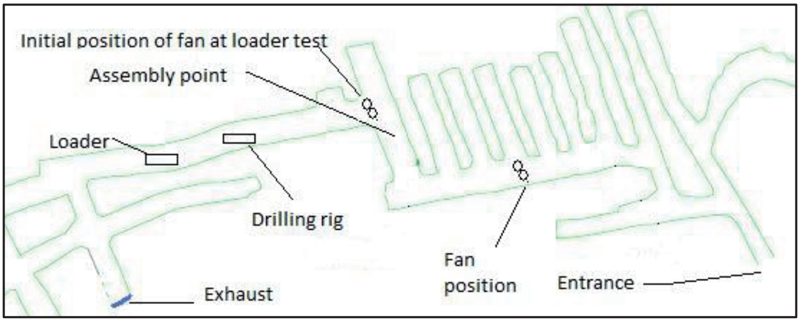

Figure 4. The test site and its immediate surroundings

In figure 5 below, the test site is shown more in detail – showing the approximate distances and the locations of measuring devices.

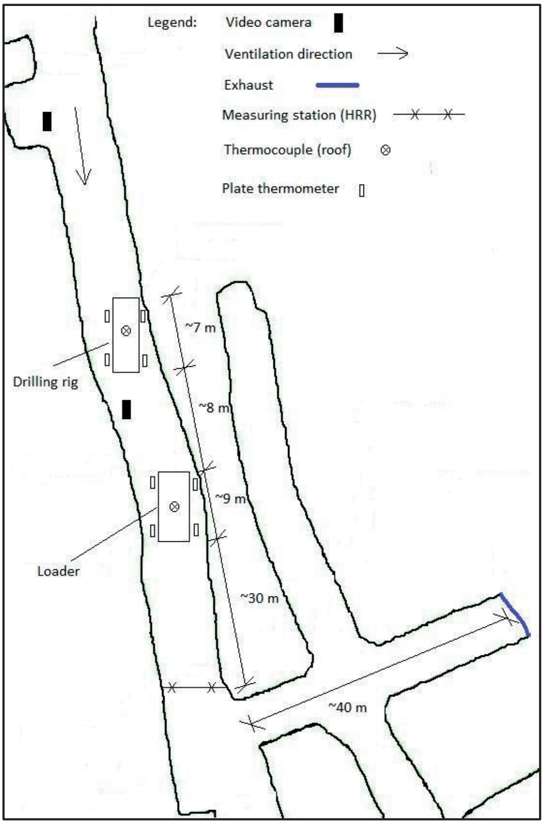

Figure 5. The test site (not to scale)

3.5.1 Instrumentation of each vehicle

On each vehicle a number of thermocouples (eight thermocouples in the case of the wheel loader and 17 in the case of the drilling rig) were placed on the combustible components: tyres, hoses, cables and the interior of the cab. Four plate thermometers were placed at the ground at each tyre during the tests in order to measure the heat flux at the locations. See table 5 and 6 for more information regarding the thermocouples and the plate thermometers.

Table 5. The instrumentation of the wheel loader

Id #	Specification of instrument	Position
Tc11	0.5 mm	Tyre, right, rear
Tc12	0.5 mm	Tyre, right, front
Tc13	0.5 mm	Tyre, left, rear
Tc14	0.5 mm	Tyre, left, front

Id #	Specification of instrument	Position
Tc15	0.5 mm	Hydraulic hoses in the rear, left side
Tc16	0.5 mm	Hydraulic hoses at the waist
Tc17	0.5 mm	Interior of cab, ceiling
Tc18	0.5 mm	Interior of cab, driver seat
PTC19		Tyre, right, rear. In line with the rear edge of the tyre; facing the vehicle; 0.5 m from the tyre; 0.4 m from the ground.
PTC20		Tyre, right, forward. In line with the rear edge of the tyre; facing the rear of the vehicle; 0.5 m from the tyre; 0.44 m from the ground.
PTC21		Tyre, left, rear. In line with the rear edge of the tyre; facing the vehicle; 0.43 m from the tyre; 0.4 m from the ground.
PTC22		Tyre, left, forward. In line with the rear edge of the tyre; facing the rear of the vehicle; 0.5 m from the tyre; 0.44 m from the ground.

Table 6. The instrumentation of the drilling rig

Id #	Specification of instrument	Position
Tc11	0.5 mm	Tyre, right, rear
Tc12	0.5 mm	Tyre, right, front
Tc13	0.5 mm	Tyre, left, rear
Tc14	0.5 mm	Tyre, left, front
Tc15	0.5 mm	Hydraulic hoses in the rear, right side
Tc16	0.5 mm	Cable reel, left, rear
Tc17	0.5 mm	Interior of cab, ceiling
Tc18	0.5 mm	Interior of cab, driver seat
PTC19		Tyre, right, rear. In line with the rear edge of the tyre; facing the vehicle; 0.5 m from the tyre; 0.4 m from the ground.
PTC20		Tyre, right, front. In line with the rear edge of the tyre; facing the rear of the vehicle; 0.5 m from the tyre; 0.4 m from the ground.
PTC21		Tyre, left, rear. In line with the rear edge of the tyre; facing the vehicle; 0.5 m from the tyre; 0.4 m from the ground.
PTC22		Tyre, left, front. In line with the rear edge of the tyre; facing the rear of the vehicle; 0.5 m from the tyre; 0.4 m from the ground.
Tc23	0.5 mm	Hydraulic hoses, at the waist, lower part, right
Tc24	1.5 mm	Hydraulic hoses, at the waist, upper part, left
Tc28	0.5 mm	Wheelhouse, rear part, right side, inside of the tyre
Tc29	0.5 mm	Wheelhouse, rear part, left side, inside of the tyre
Tc30	0.5 mm	Bundle of hydraulic hoses, between the front wheels
Tc31	0.5 mm	Bundle of hydraulic hoses on the boom, middle part, right side
Tc32	0.5 mm	Bundle of hydraulic hoses on the boom, front part, right side
Tc33	0.5 mm	Bundle of hydraulic hoses on the boom, middle part, left side
Tc34	0.5 mm	Bundle of hydraulic hoses on the boom, front part, left side

3.5.2 Instrumentation in the mine drift

At the end of the mine drift – where all the fire gases would pass – the heat release rate was measured (see figure 5 for the position of the measuring devices). The heat release rate was measured using six thermocouples, four velocity probes and one gas analysis (O_2, CO and CO_2) positioned at different heights. See figure 6 for the heat release rate measuring device.

The temperature above each vehicle was measured with a thermocouple attached to the ceiling. A video camera was placed in the mine drift aimed at the side the each vehicle in order to record the fire behavior and the time of ignition of the combustible items. See table 7 for more information regarding the thermocouples, velocity probes and the gas analysis.

The velocity was measured using bi directional probes. A differential pressure transmitter was used in the experiments, model: FCO332-3W (±50 Pa). A M&C PMA10 set for the interval 0–30 % was used for measuring the oxygen concentration and the carbon monoxide and the carbon dioxide were measured using a Rosemount Binos 100 in the case of the wheel loader (CO: 0–10 %; CO_2: 0–30 %) and a Siemens Ultramat 22P in the case of the drilling rig (CO: 0–3 %; CO_2: 0–10 %). The sensors were connected to a 20-channel Solartron 5000 IMP logger and the data was recorded at a rate of about one scan per ten seconds.

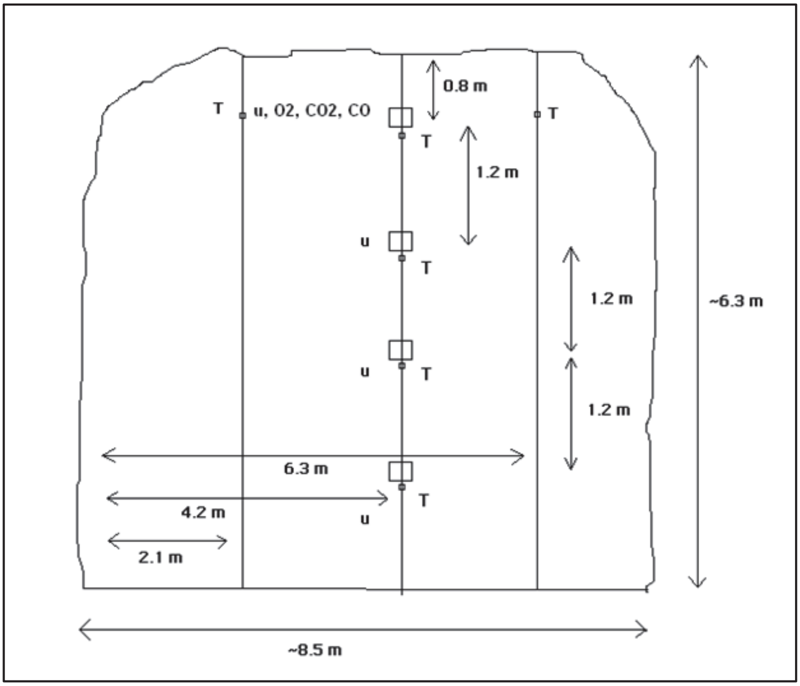

Figure 6. The heat release rate measuring station

Table 7. The instrumentation in the mine drift

Id #	Specification of instrument	Position
Tc1	1.5 mm	0.8 m down from the ceiling, left side
Tc2	1.5 mm	0.8 m down from the ceiling, middle
Diff3	Velocity probe	0.8 m down from the ceiling, middle
Tc4	1.5 mm	0.8 m down from the ceiling, right side
Tc5	1.5 mm	2 m down from the ceiling, middle
Diff6	Velocity probe	2 m down from the ceiling, middle
Tc7	1.5 mm	3.2 m down from the ceiling, middle
Diff8	Velocity probe	3.2 m down from the ceiling, middle
Tc9	1.5 mm	4.4 m down from the ceiling, middle
Diff10	Velocity probe	4.4 m down from the ceiling, middle
Tc23	0.5 mm	Attached to the ceiling, above the wheel loader
Tc24	1.5 mm	Attached to the ceiling, above the wheel loader
Tc35	1.5 mm	Attached to the ceiling, above the boom of the drilling rig
Tc36	0.5 mm	Attached to the ceiling, above the boom of the drilling rig
	Gas analysis	0.8 m down from the ceiling, middle

3.5.3 Ventilation

The test site had no fans installed in the immediate surroundings. Two months before the fire experiments the ventilation velocity in the test site was measured and found to be ~0.2–0.3 m/s. Thus the existing ventilation flow in the area would not be sufficient to ventilate all the smoke in one predetermined direction in order to obtain adequate heat release rate measurements. Additional ventilation resources were therefore needed and a mobile fan was lent from the fire and rescue services of Höga Kusten-Ådalen. The mobile fan was a Tempest fan model MGV L125, diesel powered, a diameter of 1.25 m and with a capacity of 217 000 m^3/h.

Figure 7. **The MGV L125 fan positioned in the mine drift**
Photo: Andreas Fransson

The ventilation in the mine drift was not varied during the fire experiments, with a few exceptions (see chapter 4.1). Prior to the fire experiments the question occurred whether to seal the adjacent mine drifts – with inflatable partitions – or not, in order to more effectively direct the ventilation flow to the exhaust. But when performing CFD-simulations it was concluded that partitions would not improve the flow of smoke to the exhaust, instead the partitions would increase the turbulence of the smoke.

3.6 Experimental procedure

Before the wheel loader experiment, the position of the fan was determined by measuring the air velocity at the test site for various positions of the fan. It was determined that a position at the beginning of the mine drift would provide adequate air flow in order to prevent extensive backlayering (see figure 4).

Before each test, the fuel tank was emptied to a lower level: in the case of the wheel loader to 90 liters and in the case of the drilling rig to 40 liters. An earlier performed investigation on vehicle fires in underground mines in Sweden [11] showed that in any potential full-scale fire experiments involving a larger mining vehicle, the initial fire would have to be a shielded diesel fire – for example a pool fire underneath or in the engine compartment – positioned close to larger amounts of combustibles, such as tyres, in order to achieve a fire that eventually engulf the entire vehicle. In order to fulfill this condition circular trays filled with diesel were placed underneath the fuel tank and close to one of the tyres. In the case of the wheel loader fire experiment the circular tray had a diameter of 1.1 meter and in the case of the drilling rig fire experiment 1 m. In the case of the wheel loader, the container was filled with 190 liters of diesel fuel and in the case of the drilling rig the container was filled with 60 liters.

The mobile fan was positioned at the predetermined position. The fuel cap and the cap on the hydraulic oil tank were removed and other pressurized containers were opened. The door to the cab was opened and stayed open during the experiment. The two vehicles were not warmed up before the experiment.

A hose system was laid for safety reasons and the fire and rescue service of Sala geared up. A safety briefing was held and then a smaller diesel pool fire was ignited in order to study the spread of smoke outside the exhaust. All personnel and visitors were gathered at the assembly point, the fan was started, the video camera was started, the logging of measurement data was started (two minutes before ignition) and then the ignition of the pool fire underneath the tank took place – using pieces of fiber board soaked in diesel.

In the case of the wheel loader fire experiment, the fan was started one minute before ignition and in the case of the drilling rig experiment approximately 20 minutes before ignition. A distinct pressure and flow situation was established in the case of the drilling rig experiment.

During each experiment the fire behaviour and the sequence of events were clocked and documented manually whenever it was deemed safe to be at the assembly point. After each experiment the remaining fires were extinguished, the mine drift ventilated and the parts of the ceiling affected by the fire were knocked down. After the extinguishment of the wheel loader fire, the drilling rig was driven from the entrance of the mine to its experimental position in the mine drift. The remains after each experiment were observed visually and documented – in order to record the damages to the vehicles, clues about the fire behaviour; and to determine which and estimate how much of the combustible components that actually participated in the fire. After the final experiment both vehicles were cut up and towed out from the mining drift.

4 Experimental results

In this chapter a summary of the main results related to heat release rate, maximum heat release rate, maximum temperatures, maximum ventilation velocities, maximum heat fluxes and sequence of events is presented.

4.1 The wheel loader

Approximately ten minutes after ignition, the backlayering became too large and the mobile fan had to be moved further back, closer to the entrance to the mine (see figure 4 on page 22 for the location). In table 8 a shorter description of the events during the experiment is presented.

Table 8. Time records, the experiment involving the wheel loader

Time	Event
12.30	Ignition taking place
~12.32	Right, rear tyre is ignited
~12.38	Left, rear tyre is ignited
~12.40	The mobile fan is moved to a position closer to the entrance of the mine
~12.40 to ~12.47	The smoke layer descends and ascends continuously
~12.48	Sudden increase in intensity between the two rear tyres, possibly a hydraulic hose bursting
~13.05	Right, rear tyre bursts
~13.07	Rocks start falling down from the ceiling
~13.36 to ~13.49	The smoke layer starts to descend and ascend, alternatively
~13.52	Burning hydraulic oil spurts out of the tank
~16.00	The smoke layer descends to the ground
~16.01	The smoke layer ascends from the ground
~16.30	Only the left, rear tyre and the hydraulic oil tank are burning
~16.50	The mobile fan was shifted into a lower gear. A few minutes later it was shifted back again
17.53	Measurements are stopped and the remaining fire is extinguished.

When examining the remains after the experiment, it was found that the front tyres had not participated in the fire and were therefore intact. Also, the hydraulic hoses from the waist and forward, and in some parts of the rear section behind the rear tyres, also remained intact. Other parts had participated fully in the fire.

Figure 8. The wheel loader after the fire experiment
Photo: Andreas Fransson

The heat release rate results from these tests are shown in Figure 9. The maximum heat release rate from the experiment was 15.9 MW. The maximum heat release rate was attained approximately 11 minutes after ignition.

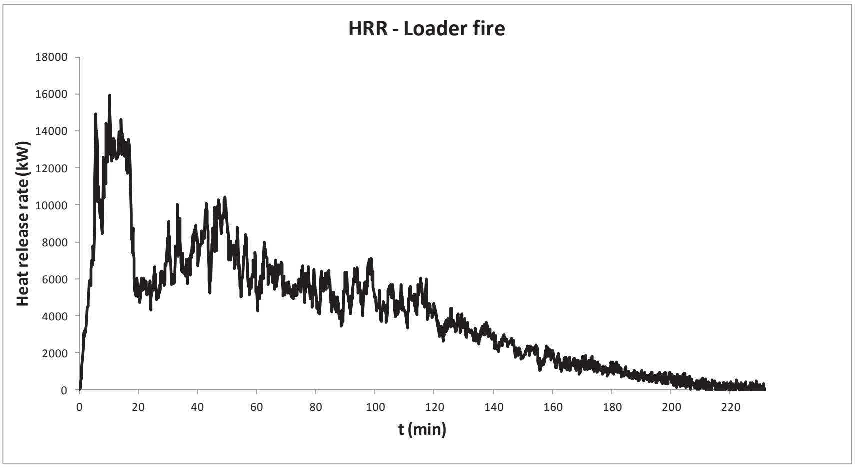

Figure 9. The heat release rate of the wheel loader

By integrating the heat release rate curve the energy content of the combustible materials consumed in the fire was calculated at 57 GJ. When summing up the energy content of the materials participating in the fire (see table 2 on page 18) the results was 50.5 GJ – noting that only 280 liters of diesel, the hydraulic oil in the tank, the cab, the rear tyres and an estimated 50 % of the hydraulic hoses (and the hydraulic oil that they contain) and electrical cables participated in the fire. The difference between the estimated energy content using an inventory and the calculated energy content thus was ~13 %. The difference is most likely due to the uncertainties when estimating the amount of combustibles available and the amount of combustibles consumed in the fire.

In figure 10, the measured oxygen level at the ceiling level and the calculated average oxygen level is presented. As noted, the calculated values follow the measured values and the measured level is generally 0.5–1.0 % lower than the corresponding calculated level, which could be expected.

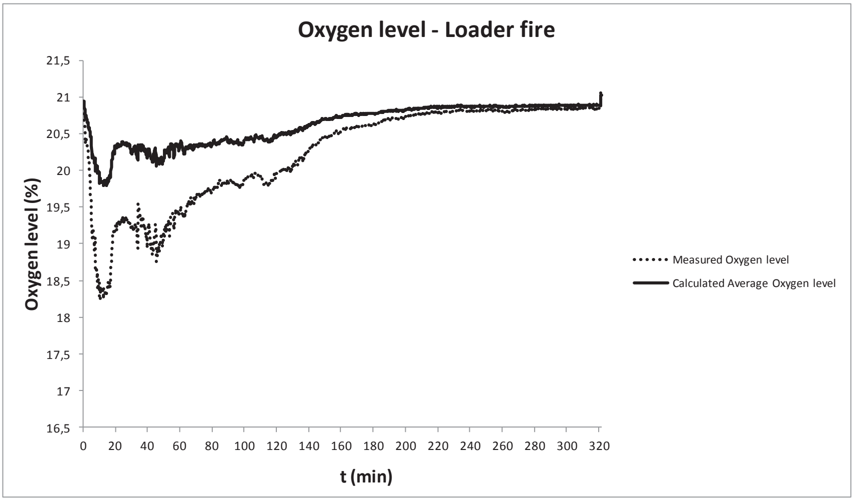

Figure 10. The measured oxygen level and the calculated average oxygen level

The maximum temperatures, maximum ventilation velocities and maximum heat fluxes are presented in table 9. In appendix C (on page 51) the full results of the temperatures, ventilation velocities and heat flux measurements are found.

Table 9. The maximum measurements of the fire experiment with the wheel loader

Id#	Value
Tc1 [K]	441
Tc2 [K]	445
Tc4 [K]	444
Tc5 [K]	355
Tc7 [K]	304
Tc9 [K]	297
Tc11 [K]	1 142
Tc12 [K]	931
Tc13 [K]	1 176
Tc14 [K]	349
Tc15 [K]	1 532
Tc16 [K]	381
Tc17 [K]	1 077
Tc18 [K]	1 103
Tc23 [K]	933
Tc24 [K]	1 504
Diff3 [m/s]	7.9

Id#	Value
Diff6 [m/s]	5.2
Diff8 [m/s]	2.2
Diff10 [m/s]	1.3
PTC19 [kW/m^2]	64.5
PTC20 [kW/m^2]	13.6
PTC21 [kW/m^2]	29.4
PTC22 [kW/m^2]	6.9

The average ventilation velocity before ignition was in the interval 0.02–0.4 m/s. The average ventilation velocity at the time of ignition was measured at 0.3 m/s. The average ventilation velocity between ignition and the time of maximum heat release rate was in the interval 0.3–2.2 m/s.

A minimum oxygen level was registered at 18.2 %. A maximum carbon monoxide level was registered at 0.09 % and the maximum carbon dioxide level at 1.87 %. Due to the high minimum oxygen level and fairly low maximum level of the carbon monoxide, the fire was most likely not ventilation controlled.

Thermocouples Tc15 and Tc17 stopped functioning after approximately 40 minutes from the time of ignition. Thermocouple Tc16 stopped functioning after approximately 50 minutes, Tc23 stopped after approximately 17 minutes and Tc24 after approximately 37 minutes. Plate thermometers PTC19 and PTC20 stopped functioning after approximately 40 minutes and PTC22 after approximately 3 hours and 20 minutes.

4.2 The drilling rig

In table 10, a shorter description of the events during the experiment is presented.

Table 10. Time records, the experiment involving the drilling rig

Time	Event
12.30	Ignition taking place
~12.32	Both rear tyres are ignited. Spreading further to hydraulic hoses in the rear, upper part
~12.42	Right, forward tyre is ignited
~12.42	Sudden increase of intensity, most likely the right rear tyre bursts
~12.47	The smoke layer descends down to the ground level
~12.53	The smoke layer ascends from the ground level
~12.56	Sudden increase of intensity, most likely the right front tyre bursts
~13.00	Most likely the left front tyre bursts
~14.30	The water hose in the rear is being ignited
14.55	Measurements are stopped and the extinguishing of the remaining fire takes place

When examining the remains after the experiment, it was found that a smaller portion of the hydraulic oil did not participate in the fire. Except for the hydraulic hoses (approximately two meters in front of the cab and forward), the amount of hydraulic oil mentioned above and a major part of the low voltage cable on the cable reel, the entire vehicle had participated in the fire and the combustible material had been consumed.

Figure 11. The drilling rig after the fire experiment
Picture: Andreas Fransson

The heat release rate results from these tests are shown in figure 12. The maximum heat release rate from the experiment was 29.4 MW, and was attained after 21 minutes.

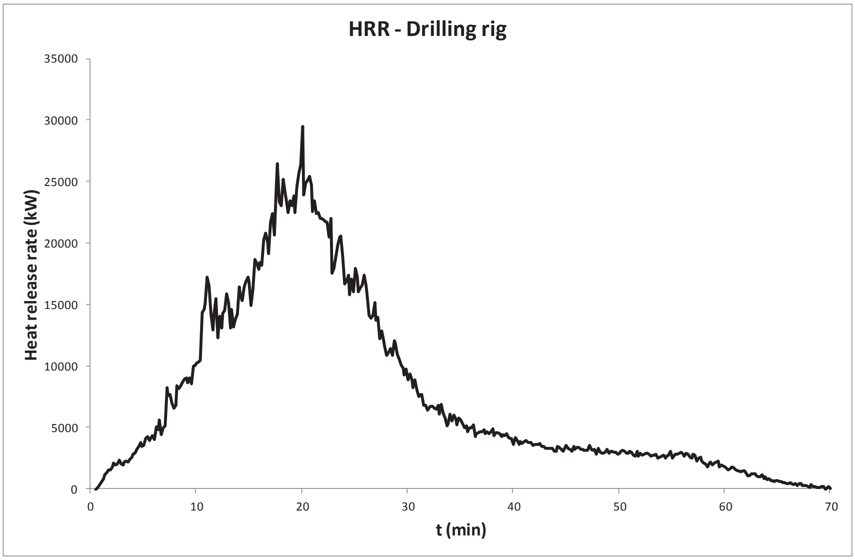

Figure 12. The heat release rate of the drilling rig

The energy content of the combustible materials consumed in the fire was calculated at 30.9 GJ. When summing up the energy content of the materials participating in the fire (see table 4 on page 20) the result was 32.5 GJ – noting an estimated 70 % of the hydraulic oil, 600 m of the hydraulic hoses, and 600 m of electrical cables participated in the fire. The difference between the estimated energy content using an inventory and the calculated energy content was ~5 %. The difference is most likely due to the same uncertainties as in the case of the wheel loader, i.e. the estimations of the amount of combustibles available and the amount of combustibles consumed in the fire.

In figure 13, the measured oxygen level at the ceiling level and the calculated average oxygen level is shown. The calculated values may be considered to follow the fluctuations of the measured values, with a genereal difference of ~1.0 % lower measured oxygen level than the calculated level.

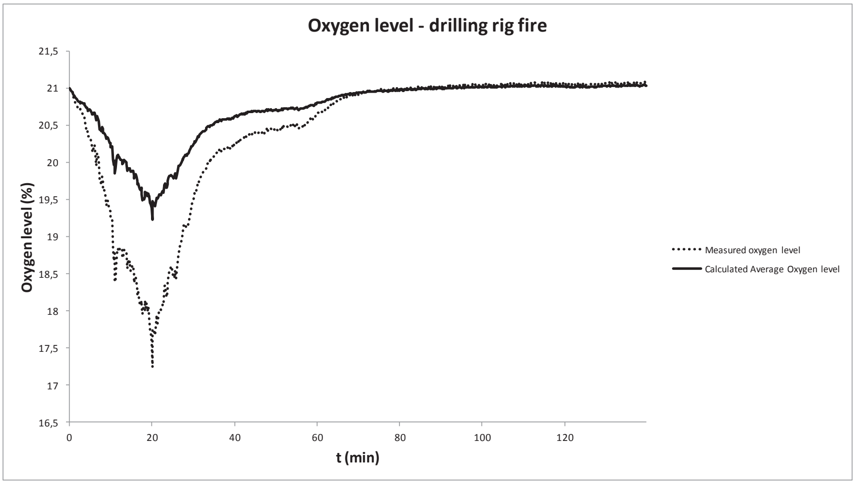

Figure 13. The measured oxygen level and the calculated average oxygen level

The maximum temperatures, maximum ventilation velocities and maximum heat fluxes are found in table 11. In appendix D (on page 57), the full results of the temperatures, ventilation velocities and heat flux measurements are found.

Table 11. The maximum measurements of the fire experiment with the drilling rig

Id#	Value
Tc1 [K]	455
Tc2 [K]	471
Tc4 [K]	458
Tc5 [K]	387
Tc7 [K]	318
Tc9 [K]	309
Tc11 [K]	1 341
Tc12 [K]	1 097
Tc13 [K]	1 239
Tc14 [K]	1 251
Tc15 [K]	986
Tc16 [K]	295
Tc17 [K]	1 327
Tc18 [K]	1 105
Tc23 [K]	1 343
Tc24 [K]	1 146
Tc28 [K]	1 341
Tc29 [K]	1 258

Id#	Value
Tc30 [K]	1 457
Tc31 [K]	1 346
Tc32 [K]	1 499
Tc33 [K]	1 319
Tc34 [K]	1 473
Tc35 [K]	732
Tc36 [K]	709
Diff3 [m/s]	12.8
Diff6 [m/s]	9.1
Diff8 [m/s]	2.4
Diff10 [m/s]	2.1
PTC19 [kW/m^2]	37.5
PTC20 [kW/m^2]	56.1
PTC21 [kW/m^2]	34.6
PTC22 [kW/m^2]	47.6

Before ignition, the average ventilation velocity was in the interval 1.2–1.4 m/s and at the time of ignition it was at 1.3 m/s. Between ignition and the time of maximum heat release rate, the average ventilation velocity was in the interval 1.1–2.6 m/s. A minimum oxygen level was registered at 17.2 % and a maximum carbon dioxide level at 2.37 %. The carbon monoxide levels cannot be presented as a measuring error occurred.

Thermocouples Tc12 stopped functioning after approximately 12 minutes from the time of ignition. Thermocouple Tc15 stopped functioning after approximately 34 minutes, Tc18 after approximately 9 minutes, Tc24 after approximately 14 minutes, Tc31 after approximately 1 hour and 40 minutes, Tc32 after approximately 45 minutes, Tc33 after approximately 25 minutes and PTC22 stopped functioning after approximately 10 minutes.

5 Discussion of results

5.1 Fire experiment with the wheel loader

The burn off time of the diesel pool fire was calculated to ~43 minutes (assuming a regression rate of 0.066 kg/s·m² (deep pool)). Assuming a maximum heat release rate per unit area of 1.33 MW/m² [12] (thick fuel bed), the maximum heat release rate of the diesel pool fire was calculated to 1.26 MW. Be aware that the longitudinal ventilation will increase the maximum heat release rate further more. The total outer surface of each loader tyre was calculated to approximately 13 m² (also including the outer surface that is not in contact with the ground). Assuming a maximum heat release rate per exposed tyre surface area of 0.25 MW/m² [7] and assuming that the longitudinal ventilation velocity would increase the maximum heat release rate with a factor 2 [13], the maximum heat release rate of each loader tyre was calculated to 6.5 MW. If assuming that the entire right rear tyre is involved in the fire at the time of maximum heat release rate, and that approximately 50 % of the left rear tyre is involved in the fire, the tyre fires and the diesel fire would have a heat release rate of ~11 MW and the hydraulic hoses, cables and hydraulic oil would contribute with the remaining 5 MW.

The sudden and temporary decrease in the ventilation velocities and heat release rate approximately 10 minutes after ignition can be related to the change of position of the mobile fan, as the fan was geared down temporarily during the transport.

At the time of observed ignition of the left rear tyre the measured heat flux at the tyre was ~5 kW/m², which should be considered too low a figure for ignition of the tyre. The reason why ignition occurred at this stage could be that the plate thermometer was shielded from the pool fire and that the ignition initially took part in the inner parts of the tyre. When studying the temperature at the rim of the same tyre (thermocouple Tc13), it can be seen that the temperature was fairly low until approximately 2 hours after ignition. Then the temperature made a sudden jump up to ~1 200 K (at that time the plate thermometer recorded a heat flux of approximately 20 kW/m²). This observation further strengthens the hypothesis that the ignition of the left rear tyre started in the inner parts, shielded from the plate thermometer and slowly spread outwards.

The maximum measured heat fluxes at the front tyres were 13.6 kW/m² (right tyre) and 6.9 kW/m² (left tyre). The values did not exceed the critical heat flux of natural rubber at 17.1 kW/m² [14] and ignition never occurred.

The hydraulic hoses in the waist never ignited and when reading the maximum measured temperature at the hydraulic hoses in the waist at 381 K, it is obvious that the temperatures in the waist never allowed the fire to spread further.

The resulting heat release rate curve of the wheel loader displays a fire that is dominated by initially the sudden increase when the first tyre is engulfed by flames and then by the slowly declining heat release rates of the large tyres of the vehicle. Still, the stop of fire spread from the waist and forward clearly shortened the duration of the fire considerably.

5.2 Fire experiment with the drilling rig

The burn off time of the diesel pool fire was calculated to ~17 minutes. Thus the diesel pool fire would not contribute to the heat release rate at the time of maximum heat release rate. Assuming a maximum heat release rate per unit area of 1.33 MW/m², the maximum heat release rate of the diesel pool fire was calculated to 1.04 MW. The total outer surface of each loader tyre was calculated to approximately 3 m² and assuming that the longitudinal ventilation velocity would increase the maximum heat release rate with a factor 2 [13], the maximum heat release rate of each drilling rig tyre was calculated to 1.5 MW. The total length of the hydraulic hoses on the drilling rig is approximately 1 000 meters and they have an average outer diameter of 22 mm. If assuming that at the time of maximum heat release rate, half of the total length of hydraulic hoses are participating in the fire, and using a heat release rate per unit area of 150 kW/m² (based upon the results from the cone calorimeter experiments), the total heat release rate of the hydraulic hoses would be approximately 5.6 MW. Increasing the heat release rate with a factor 2, due to the longitudinal ventilation, the heat release rate of the hydraulic hoses would be 11.2 MW. If summing up the heat release rate of the tyres and the hydraulic hoses (the diesel pool fire had burned off at the time of the maximum heat release rate), the heat release rate would be 17.2 MW. This would mean that the fire in the hydraulic oil, the cab and the electrical cables would contribute with the remaining 11.8 MW.

When studying the heat release rate curve, a sudden increase can be seen after approximately 13 minutes. This is most likely due to the ignition of the rightfront tyre. The plate thermometer at the right front tyre registered a sudden increase of the incident heat flux to 17.1 kW/m² after approximately 13 minutes from ignition, which is about the time of ignition of the tyre.

The maximum temperature at the cable reel in the rear was measured at 295 K and only a minor part of the power cable participated in the fire, which is not surprising with respect to the measured maximum temperature. The maximum temperatures of the measuring points along the boom all exceeded 1 300 K, it is unclear why ignition did not take place in the front parts of the hydraulic hose.

The resulting heat release rate curve of the drilling rig displays a fire with high heat release rates and is relatively short lived, compared to the fire in the wheel loader experiment. Practically all the combustible items were ignited in the early phases of the fire.

6 Conclusions

Two full-scale fire experiments – involving a wheel loader and a drilling rig – were carried out in an operative underground mine at Björka Mineral AB in Sala, Sweden. The aims of the report were to obtain data which can validate models to calculate the total heat release rate of mining vehicles and to produce total heat release rate curves for representative mining vehicles.

It was found in the experiment involving the wheel loader that the front part of the vehicle with front tyres etc. never ignited. The maximum measured heat fluxes at the front tyres were 13.6 kW/m^2 (right tyre) and 6.9 kW/m^2 (left tyre). The values did not exceed the critical heat flux of natural rubber at 17.1 kW/m^2 [14] and thus ignition never occurred. Furthermore the maximum temperature recorded at the hydraulic hoses in the waist was 381 K and thus the low temperatures did not allow for further fire spread. The maximum heat release rate from the experiment was 15.9 MW, which was attained approximately 11 minutes after ignition. The resulting heat release rate curve of the wheel loader fire displays a fire that is dominated by initially the sudden increase when the first tyre is engulfed by flames and then by the slowly declining heat release rates of the large tyres of the vehicle. Still, the stop of fire spread from the waist and forward clearly shortened the duration of the fire considerably. The energy content of the combustible materials consumed in the fire was calculated at 57 GJ.

Regarding the drilling rig fire experiment, it was found that the entire vehicle had participated in the fire – except for the hydraulic hoses (approximately two meters in front of the cab and forward), some amount of hydraulic oil and a major part of the low voltage cable on the cable reel. The maximum temperatures of the measuring points along the boom all exceeded 1 300 K, which makes it unclear why ignition did not take place in the front parts of the hydraulic hose. The maximum heat release rate from the experiment was 29.4 MW, which was attained after 21 minutes. The resulting heat release rate curve of the drilling rig displays a fire with high heat release rates and relatively short lived, compared with the fire in the wheel loader experiment. Practically all the combustible items were ignited in the early phases of the fire.

Further validation work should take place with respect to validating the experimental data with output data from theoretical models.

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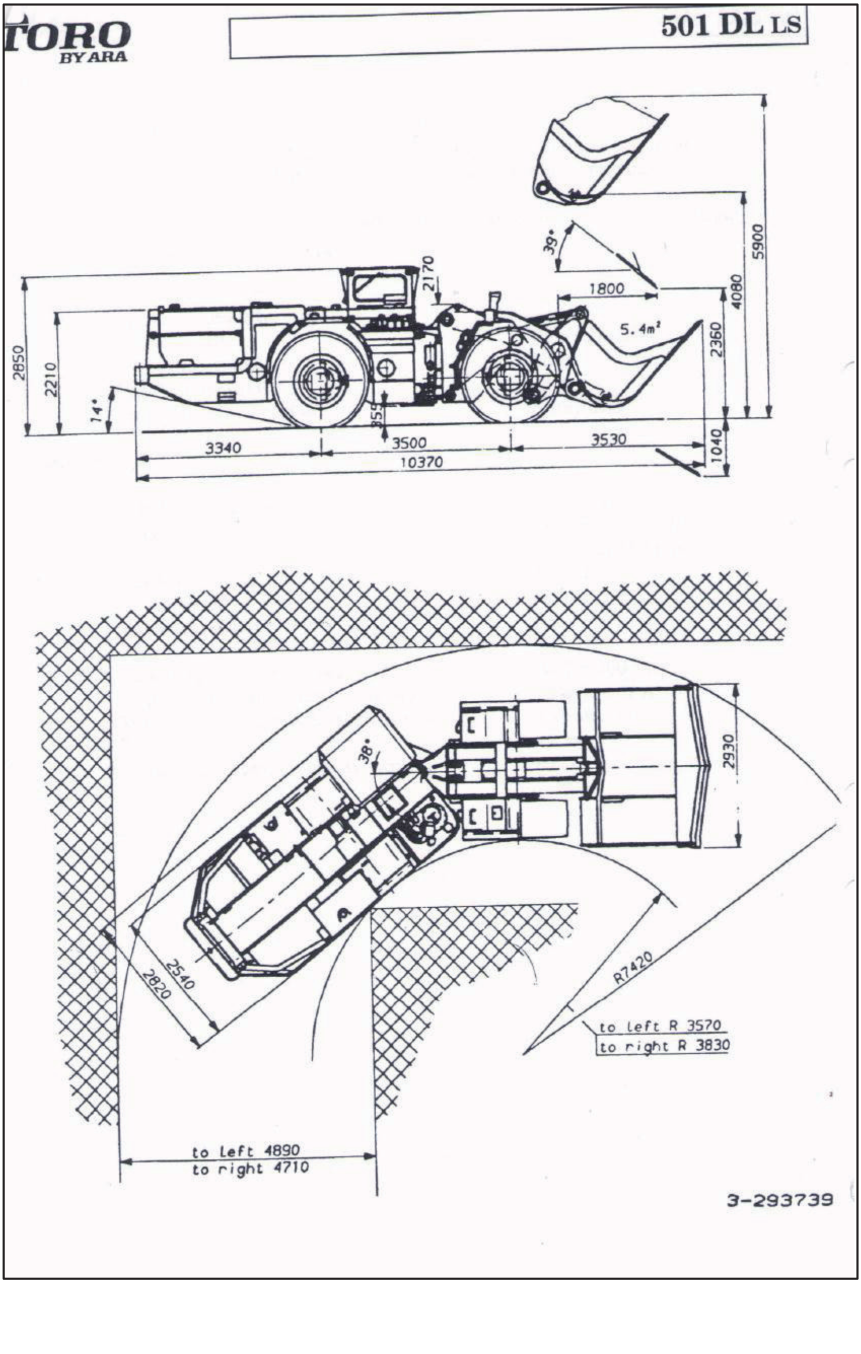
Appendix A: Specifications of the wheel loader



TORO BY ARA

501 DL LS

Bromsar

Hydraulisk, oljekyld flerskivig broms i varje hjul som färdbroms. Två separata bromskretsar. Nödbromsen användar samma broms som färdbromsen och den kontrolleras i förarhytten med en spak.

Parkeringsbromsen är en fjäderbelastad kardanskivbroms som frigörs hydrauliskt.

Huvudkomponenter	
Tryckackumulatorer	Bosch
Bromsventil	Rexroth LT07
Laddningsventil	Mico
Parkeringsbroms	ARA
Returfilter för kylning	FinnFilter

Utrustning

Arbets- och körljus	11 st. 24 V 70 W H1
Generator	Motorola 24 V 70 A
Startmotor	Bosch 24 V 9 kW
Ackumulatorer	12 V 160 Ah
Kompressor	Deutz
Vattenskrubber	ARA
Säte med luftfjädring (extrautrustning)	Be-Ge 9001A
Automatisk centralsmörjning (ext.)	Safematic / ARA
TOROTEL-fjärstyrning (extrautr.)	Estron / ARA
Pulversläckare	12 kg
Släckningsystem (extrautrustning)	Ansul

TORO BY ARA

501 DL LS

TEKNISK SPECIFIKATION

Huvuddimensioner

Totallängd		10 300 mm
Totalbredd (utan skopa)		2 810 mm
Höjd utan kabin		2 230 mm
Totalhöjd		2 850 mm

Vikt

Vikt (användbar)		36 000 kg
Totalvkt med last		50 000 kg
Axelvikt, tom	framaxel	15 950 kg
	bakaxel	20 050 kg
Axelvikt, med last	framaxel	38 350 kg
	bakaxel	11 650 kg

Kapacitet

Transportförmåga		14 000 kg
Brytningskraft,	tippcylinder	248 kN
	lyftcylinder	292 kN
Tippförmåga		26 000 kg
Skopa (SAE)		4,3 - 9,0 m³

Lyfttider för skopa

Lyfttid	8,0 s
Sänktid	6,0 s
Tipptid	2,0 s

Körhastigheter, framåt och bakåt

Växel n:o 1	5,3 km/h
2	9,0 km/h
3	15,5 km/h
4	25,5 km/h

TORO BY ARA

501 DL LS

Motor

Motor	Deutz BF12L 413 FW
Effekt	240 kW (326 hp) / 2300 r/min
Vridmoment	1160 Nm / 1600 r/min
Cylinderantal	V12
Cylindervolym	19 144 cm3
Kylsystem	luftkyld
Elektrisk utrustning	24 V
Vikt	1300 kg
Förbränning princip	fyrtaktsdieselmotor med förkammare

Kraftöverföring

Momentomvandlare	Clark C8502-91
Växellåda	Clark 5422, fyra växlar, modulering
Axlar, fram och bak	Clark 21D 3960, bakaxeln oscillerar +/- 12°
Däck	26,5 x 25 L5S
- tryck, fram	500 kPa (5,0 bar)
bak	350 kPa (3,5 bar)

Styrning

Helhydrauliskt servostyrt chassistyrning med lastkännande reglering. Vridvinkel +/- 38°. Dubbelverkande styrcylindrar (Ø 160 mm).

Huvudkomponenter	
Pump, kolvtyp	Vickers PVH98C
Servoventil	Rexroth 2TH6
Huvudventil	Rexroth 1MO22
Cylindrar (2)	ARA
Tryckinställning	
- styrhydraulik	12,0 MPa (120 bar)
- stötavlastningsventil	20,0 MPa (200 bar)

Skophydraulik

Lyft med två cylindrar (Ø 200 mm), tippning med en Ø 250 mm cylinder. Huvudventilen är servostyrd. Oljeflödet från styrhydraulikens pump leds till skophydraulikens huvudventil när styrningen inte används. Lastkännande system med variabelvolympump.

Huvudkomponenter	
Pump, kolvtyp	Vickers PVH98C
Servopump	Casappa CPL 13+13
Servoventil	Rexroth 4TH6
Huvudventil	Rexroth 2M1-32
Cylindrar	ARA
Tryckinställning	
- servohydraulik	2,5 MPa (25 bar)
- skophydraulik	19,0 MPa (190 bar)
- stötavlastningsventil	21,0 MPa (210 bar)
Hydraultank	ca. 500 l

TORO
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VOLYMER

Motor	29 l (26 l utan filter)
Kraftöverföring	ca. 50 l, kontroll vid gång
Axlarna	2 x 61,5 l (differential 42,5 l; nav 9,5 l)
Hydrauloljetank	ca. 500 l
Bränsletank	440 l
Vattentank	410 l

SERVICEDELAR

Oljefilter för motor		2 st.	470 1244
Bränslefilter		1 st.	470 1242
Bränslefilter		1 st.	470 1246
Luftfilterelement		1 st.	471 0040
Luftfilter, säkerhetspatron		1 st.	471 0041
Filterelement för kraftöverföring		1 st.	469 8047
Returoljefilter för skophydraulik		1 st.	400 4079
Returoljefilter för bromskylning		1 st.	400 4080
Luftfilter för klimatanläggning	- grov	1 st.	491 0505
	- fin	1 st.	491 0506
	- micro	1 st.	491 0507
Kilrem		2 st.	491 0270

VIKTIGT

☞ Kolla alla skarvar vid veckoservice. Reparera om läckage förekommer. Kolla också slangar.

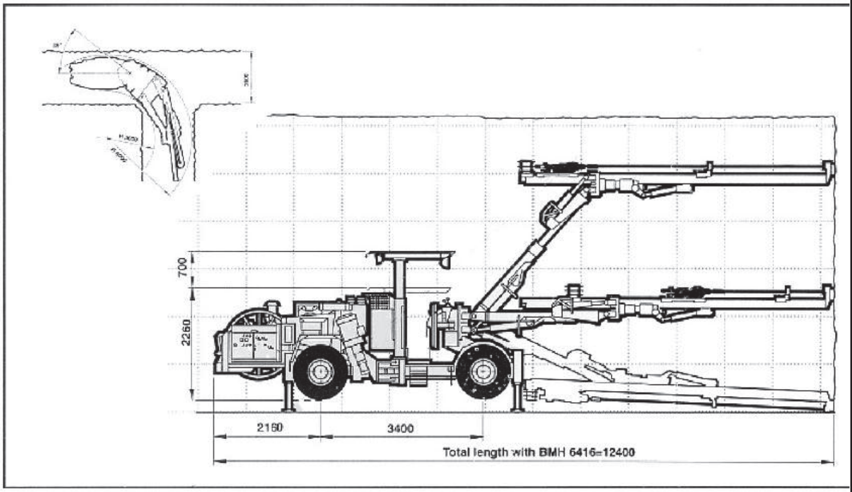
☞ Smörj tapparnas fasta bussningar vid veckoservice.

Appendix B: Specifications of the drilling rig

Technical Specification

Rocket Boomer 322-1838

High capacity hydraulic drill rig for medium sized tunnels and mine production (8-45 m^2)



Features

- Fully equipped with protective roof, cable reel and working lights, 3x500 W halogen
- Electro-hydraulic drilling with COP 1838
- Four-wheel drive with automatic diff lock in both axles
- Accurate, fast and simple positioning with BUT 32
- Precise parallel holding in all directions
- Semi-automatic collaring and anti-drill-steel-jamming for easy drilling with low drill steel cost
- Adjustable expanding shafts in all boom joints
- Central lubricated carrier frame
- Safety brakes type spring applied, hyd. release
- Water booster pump for efficient flushing
- Pump un-load function for easier start with low voltage

Main components

Rock drill	2xCOP 1838ME
Feed	2xBMH 6000-series
Boom	2xBUT 32
Power pack	ECS 18-2
Carrier	DC 17

Rock drill COP 1838ME

Drill steel	T 38
Impact power, max	20 kW
Impact rate	60 Hz
Lub. air consump. (at 2 bar)	5 l/s
Water requirement	1.1 l/s
Rotation system	separate rotation
Rotation speed	0-300 rpm
Weight	171 kg
Sound level	106 dB(A)

Feeds

	BMH 6412	BMH 6414	BMH 6416
Total length, mm	5290	5880	6490
Hole depth, mm	3440	4030	4640
Drill steel length, mm	3700	4305	4915
Weight,incl.rock drill,kg	580	610	650
Feed force, kN	20.0	20.0	20.0

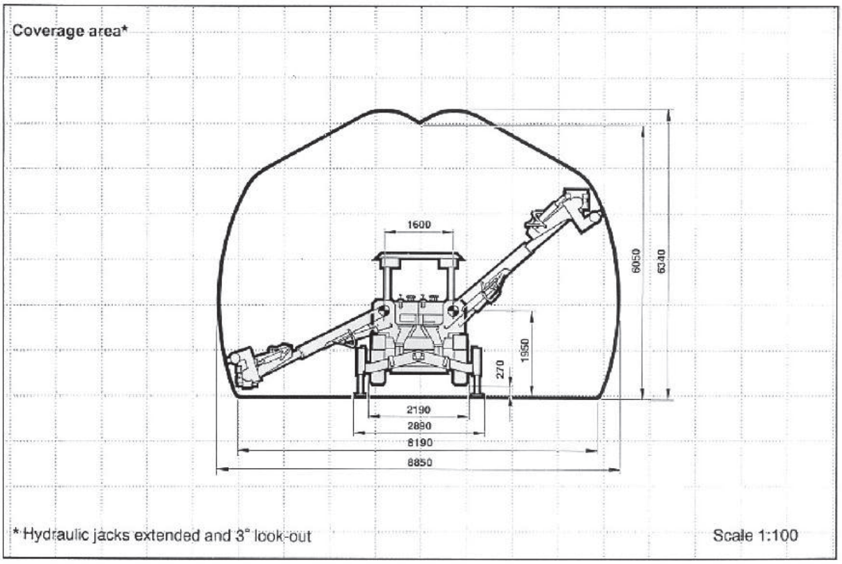
Boom BUT 32

Weight, boom only	1985 kg
Feed extension	1800 mm
Boom extension	1250 mm
Feed roll-over	360 degrees
Parallel holding	Complete

Drilling system ECS 18-2

Control system	electrical, PLC-based
Pump motors	2x55 kW
Hydraulic pumps	variable pumps for percussion constant flow pumps for rotation and dampening
System pressure, impact mechanism	150-250 bar
Hydraulic oil tank,volume	350 litres
Hydraulic oil type	mineral
Compressor, type	LE 8
Water booster, capacity	300 l/min at 14 bar boost

Rocket Boomer 322-1838



Carrier

Type	DC 17
Engine	Deutz F6L 912W 66kW (88 hpDIN)at 2500rpm
Electrical system	24 V
Max. travel speed	13 km/h
Transmission	Hydrodynamic, Clark 12000
Axles	Hurth with wet discbrakes
Hill climbing ability	1:4
Braking system	All hydraulic brakes, with parking and emergency brake. Two independent circuits
Tyre dimensions	Boom and engine axles 13.00x20 PR 18
Steering system	Hydrostatic power steering

Electrical system

Total el. consumption		120 kW
Voltage		380-660 V
Frequency		50 or 60 Hz
Rec. size of el. cable,		
380-420 V	special reel	4x95 mm^2, 90m
440-550 V		4x70 mm^2, 75m
660 V		4x50 mm^2, 100m

Dimensions and weights

Height with protective roof, transp.	2250 mm
Height with protective roof, drilling	2950 mm
Width	2190 mm
Length (with BMH 6416)	12400 mm
Turning radius, inner	3600 mm
outer	6000 mm
Gross weight	18400 kg

Optional equipment

- Silenced operator's cab
- Cable
- Exhaust water scrubber
- Exhaust catalyzer
- Telescopic feed BMHT 6000-series
- Extension drilling set, BSH 110
- Rod Adding System RAS
- Inclination instrument TAS
- Boom lubrication system
- Hydraulic Swellex pump
- Electric oil filling pump
- Electric outlet for accessories, 32 Amp.
- 1000 V electric system
- Water flow guard
- Built-in fire extinguisher system
- Hole blowing kit

Atlas Copco

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The manufacturer reserves the right to make modifications without prior notice.

Appendix C: Temperatures, ventilation velocities and heat flux measurements in the wheel loader fire experiment

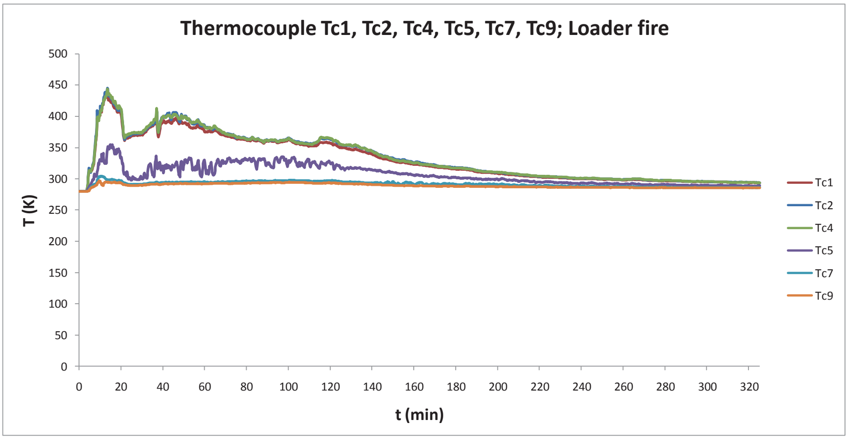


Figure C.1 The results of thermocouple Tc1, Tc2, Tc4, Tc5, Tc7 and Tc9 at the loader fire

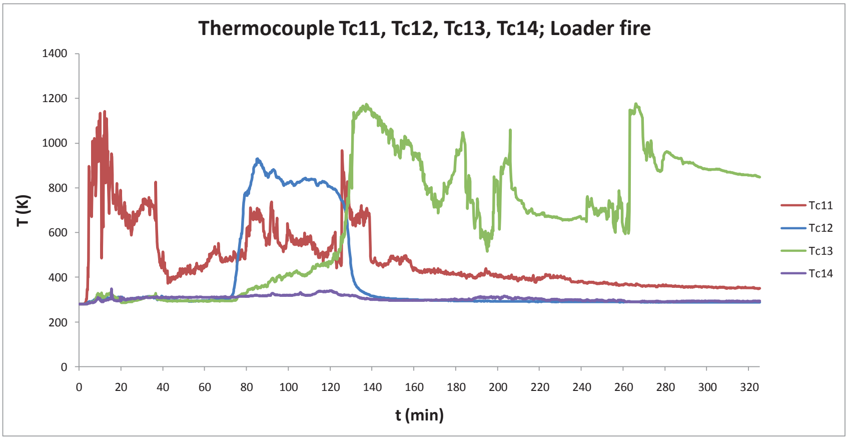


Figure C.2 The results of thermocouple Tc11, Tc12, Tc13 and Tc14 at the loader fire

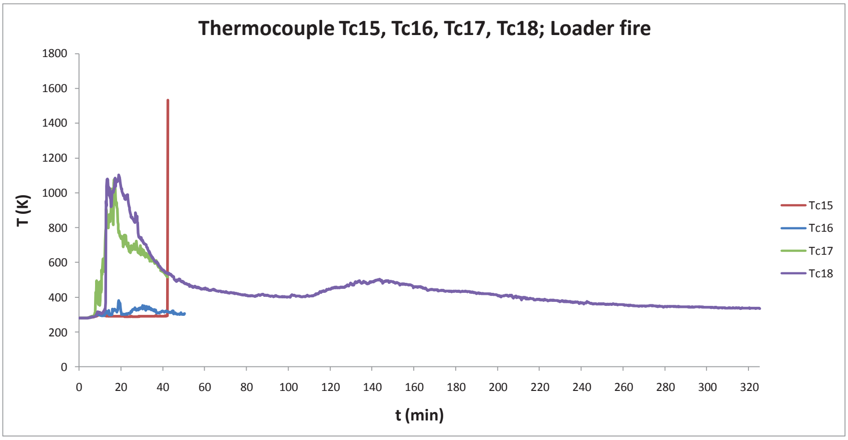


Figure C.3 The results of thermocouple Tc15, Tc16, Tc17 and Tc18 at the loader fire

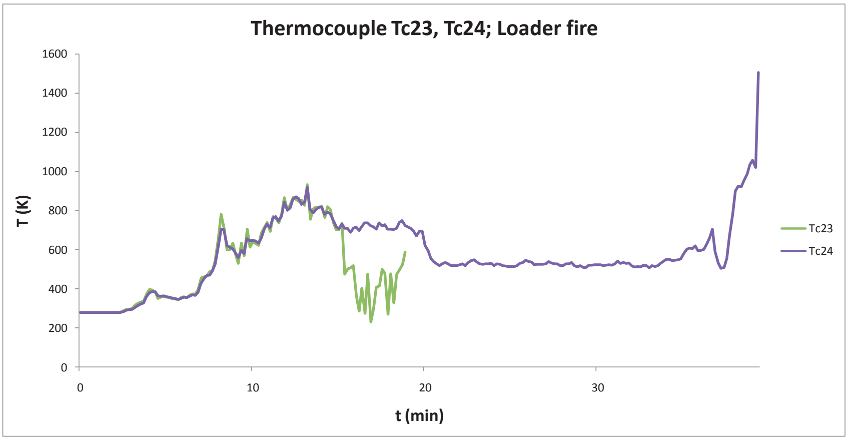


Figure C.4 The results of thermocouple Tc23 and Tc24 at the loader fire

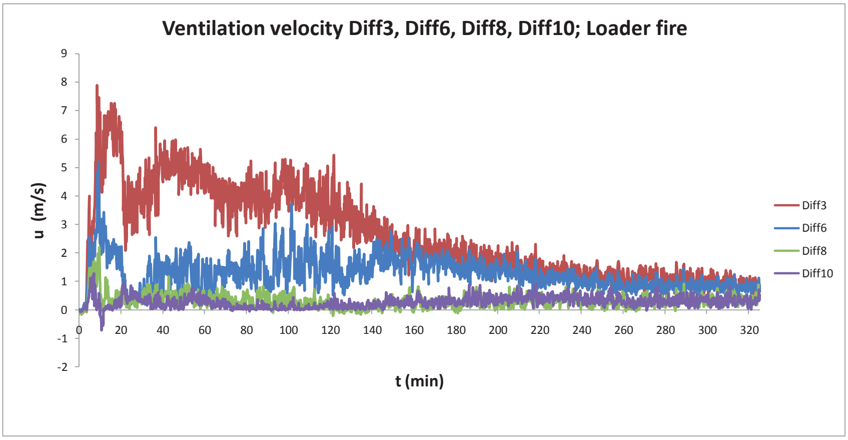


Figure C.5 The results of velocity probe Diff3, Diff6, Diff8 and Diff10 at the loader fire

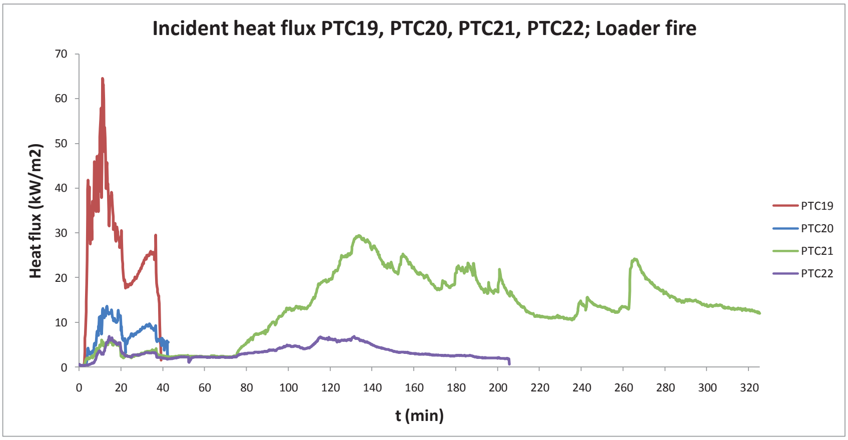


Figure C.6 The results of plate thermometer PTC19, PTC20, PTC21 and PTC22 at the loader fire

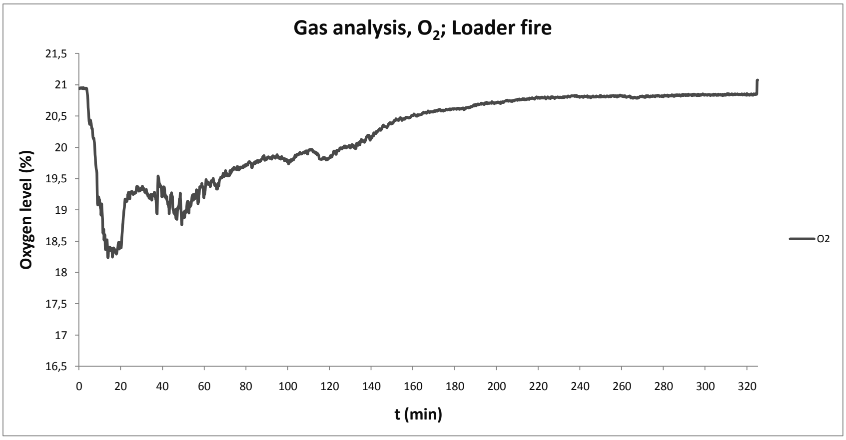


Figure C.7 The results of gas analysis O_2 measurements at the loader fire

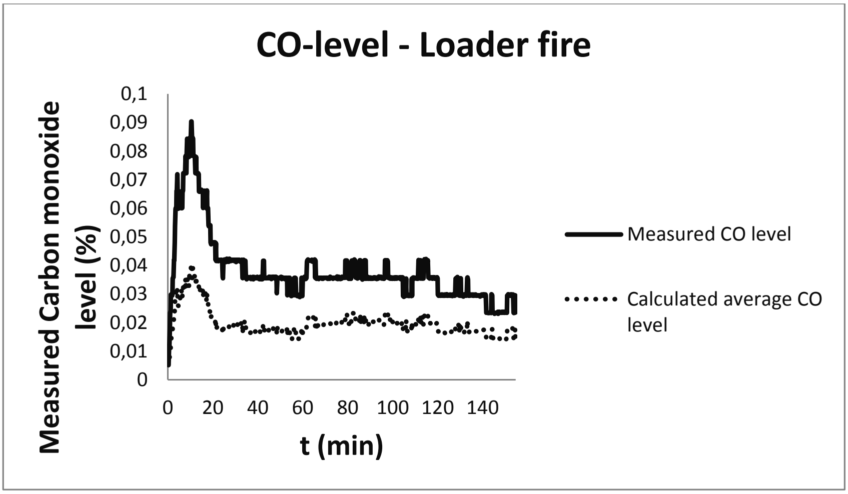


Figure C.8 The results of gas analysis CO measurements and calculations at the loader fire

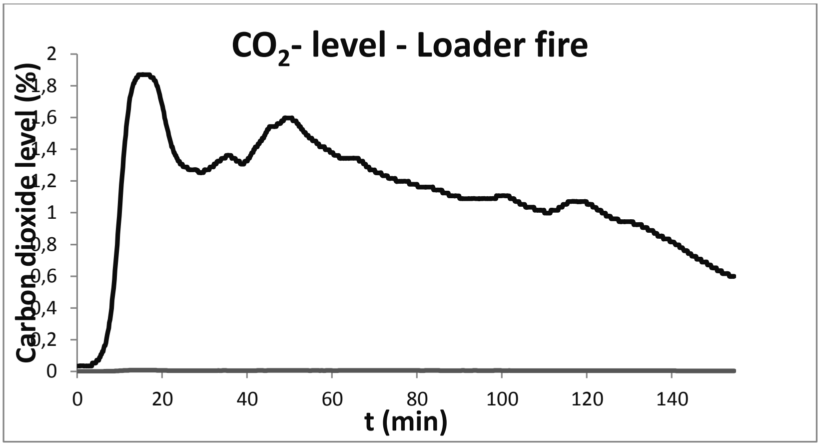


Figure C.9 The results of gas analysis CO_2 measurements at the loader fire

Appendix D: Temperatures, ventilation velocities and heat flux measurements in the drilling rig fire experiment

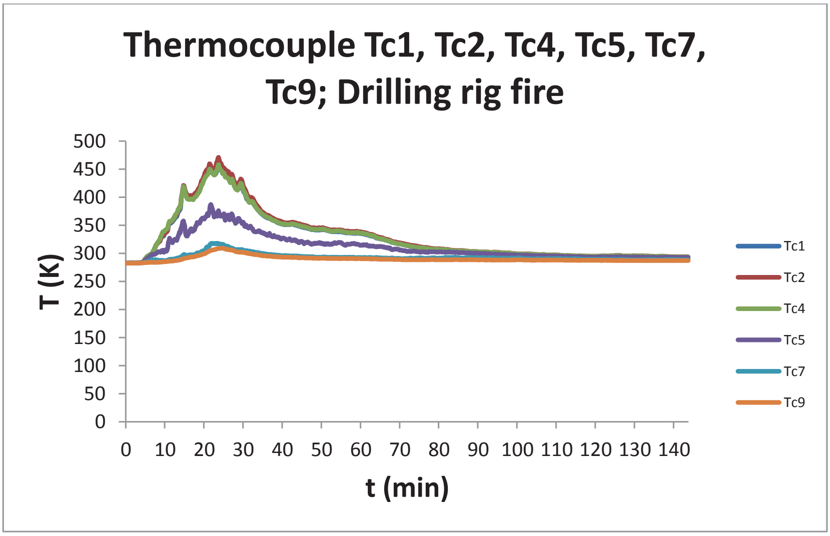


Figure D.1 **The results of thermocouple Tc1, Tc2, Tc4, Tc5, Tc7 and Tc9 at the drilling rig fire**

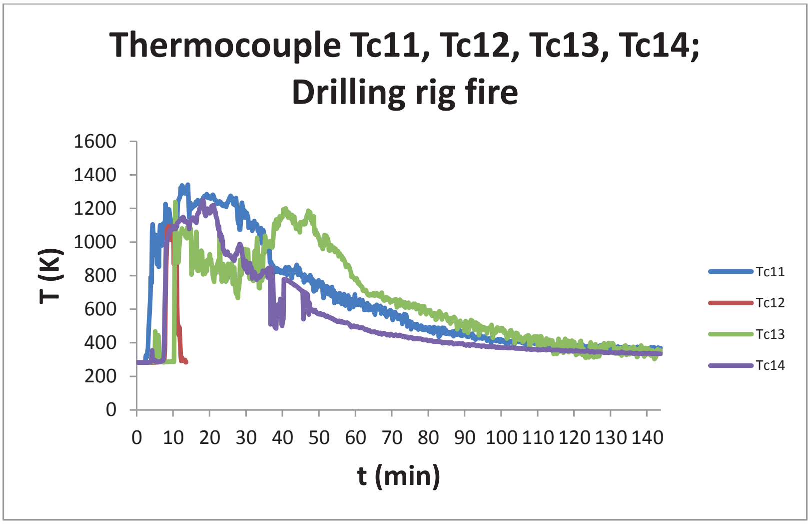


Figure D.2 **The results of thermocouple Tc11, Tc12, Tc13 and Tc14 at the drilling rig fire**

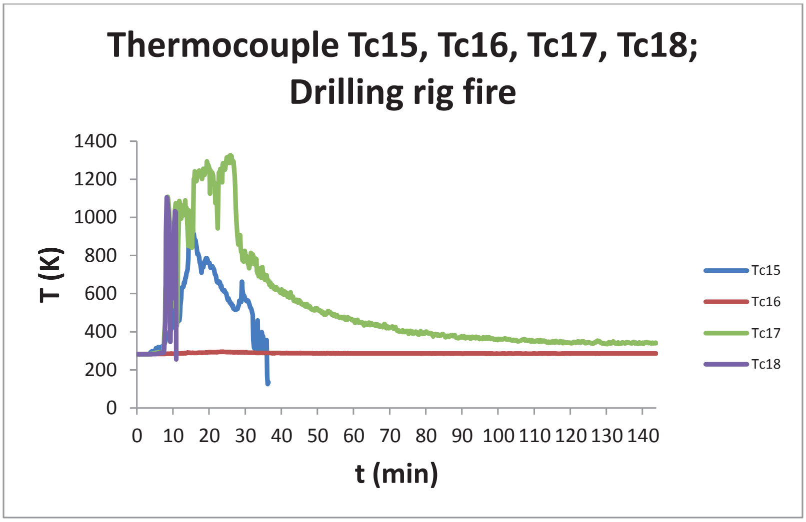


Figure D.3 **The results of thermocouple Tc15, Tc16, Tc17 and Tc18 at the drilling rig fire**

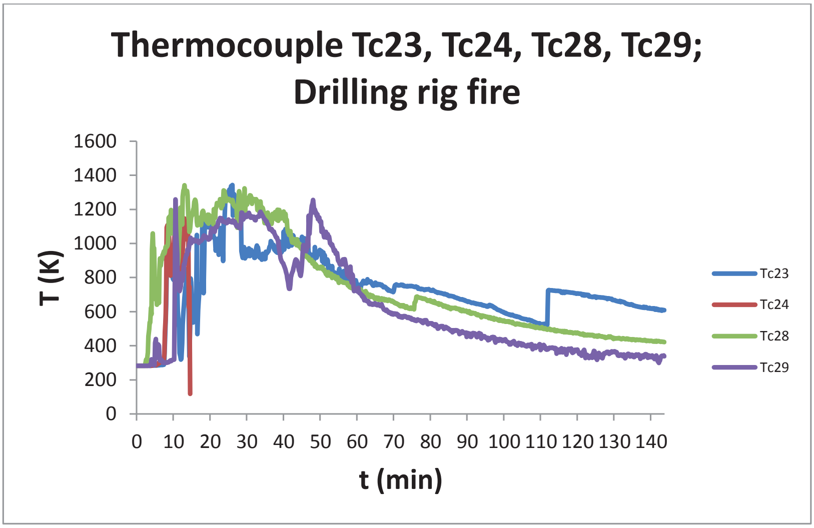


Figure D.4 The results of thermocouple Tc23, Tc24, Tc28 and Tc29 at the drilling rig fire

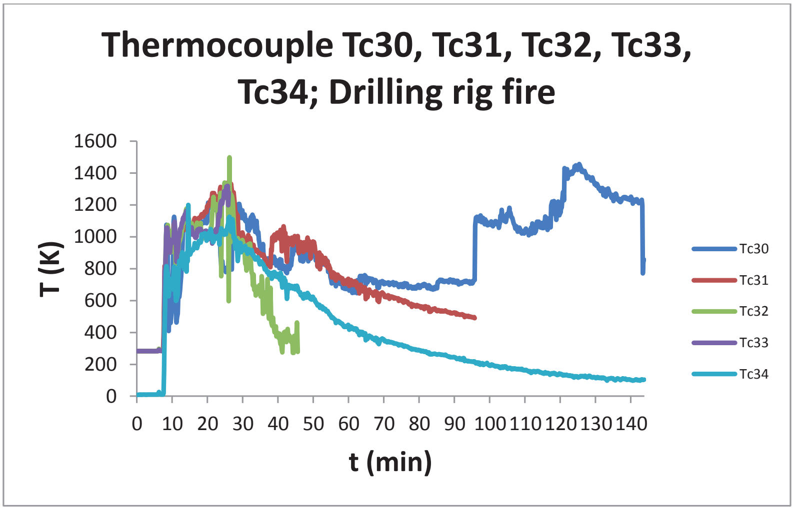


Figure D.5 The results of thermocouple Tc30, Tc31, Tc32, Tc33 and Tc34 at the drilling rig fire

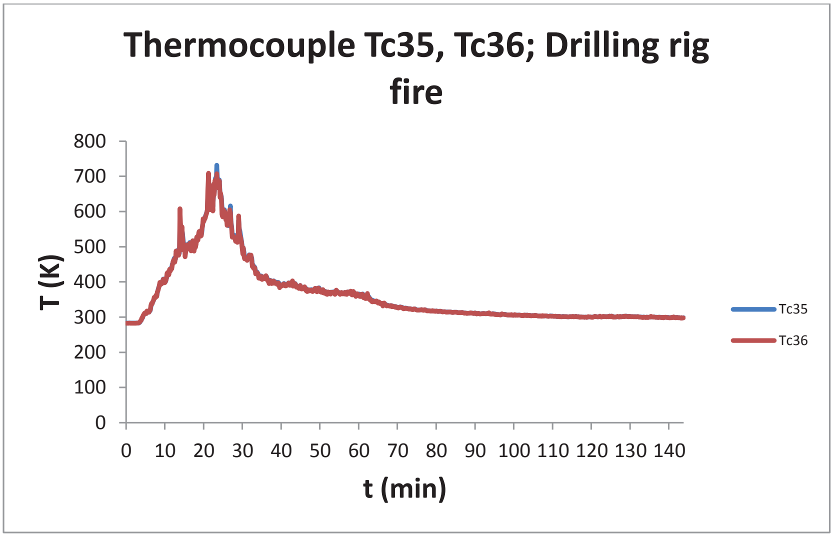
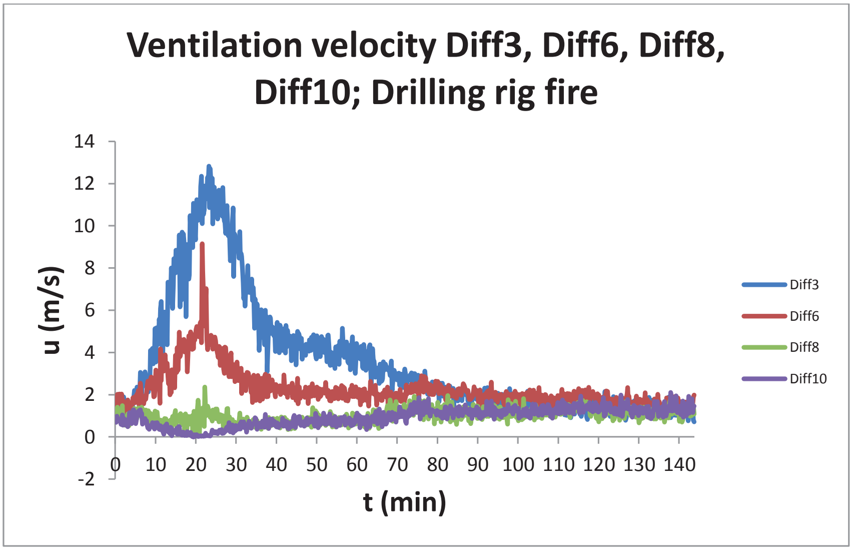


Figure D.6 **The results of thermocouple Tc35 and Tc36 at the drilling rig fire**



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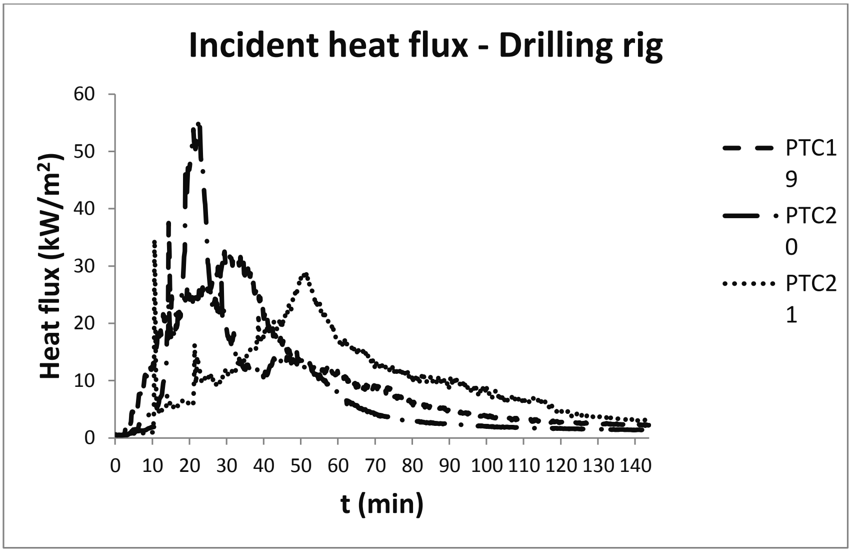

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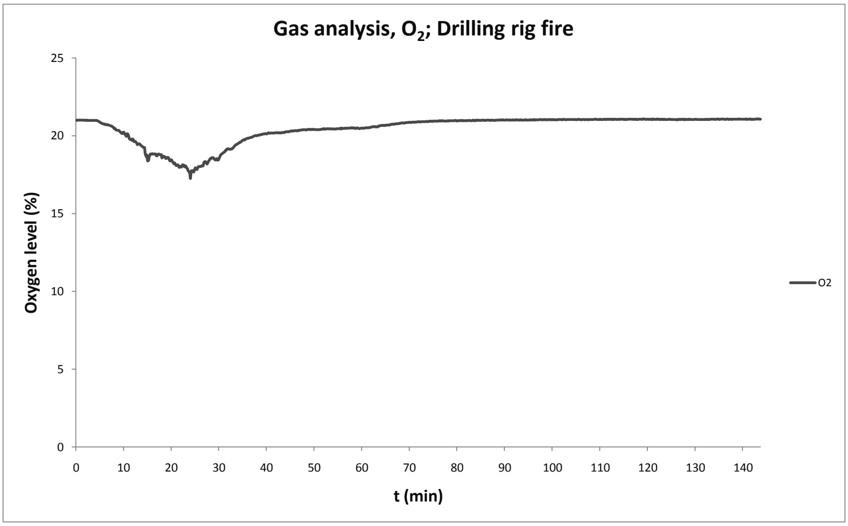

Figure D.9 **The results of gas analysis O_2 at the drilling rig fire**

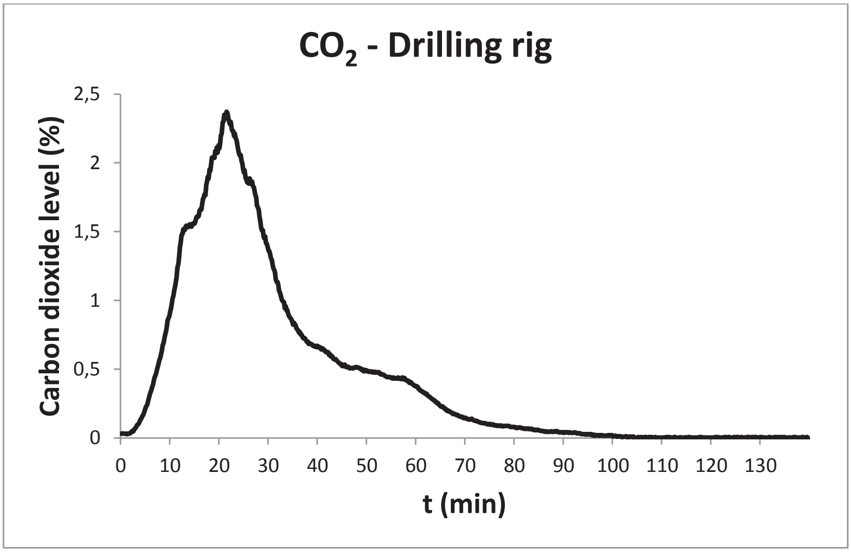

Figure D.11 The results of gas analysis CO_2 at the drilling rig fire

FULL-SCALE FIRE EXPERIMENTS WITH MINING VEHICLES IN AN UNDERGROUND MINE

This report comprises two full scale fire experiments in a mine drift in Sala, Sweden, involving a loader and a drilling rig respectively.

It was found in the experiment involving the loader that the front part of the vehicle never ignited. The maximum measured heat fluxes at the front tyres were found to never exceed the critical heat flux of natural rubber and thus ignition never occurred. Furthermore, the maximum temperature recorded at the hydraulic hoses in the waist was 381 K, thus the low temperatures did not allow for further fire spread. The maximum heat release rate from the experiment was 15.9 MW and it was attained approximately 11 minutes after ignition. The resulting heat release rate curve of the wheel loader fire displays a fire that is dominated by initially the sudden increase when primarily the first tyre is engulfed by flames and then by the slowly declining heat release rates of the large tyres of the vehicle. Still, the stop of fire spread from the waist and forward clearly shortened the duration of the fire considerably.

It was found in the experiment with the drilling rig that the entire vehicle had participated in the fire and the combustible material had been consumed – except for the hydraulic hoses approximately two meters in front of the cab and forward, some amount of hydraulic oil and most of the low voltage cable on the cable reel. The maximum heat release rate from the experiment was 29.4 MW and it was attained after 21 minutes. The resulting heat release rate curve of the drilling rig displays a fire with high heat release rates and relatively short lived.

The research project “Fire spread and heat release rate of underground mining and tunnelling vehicles – BARBARA”, is conducted by a research group at Mälardalen University. The project is aimed at improving fire safety in mines and tunnels during construction in order to obtain a safer working environment for the people working for the mining companies, as well as the tunnelling companies in Sweden or for visitors in mines open to the public.

A study from MERO

This study is published within the MERO research area (Mälardalen Energy and Resource Optimization) at Mälardalen University. The research within MERO is directed towards various aspects of a sustainable society, with particular focus on the optimization and protection of community resources and infrastructure. The research groups within the area are mainly specialized in energy efficiency, resource conservation, design of systems and processes, remediation of contaminated land and fire safety in underground facilities. A common denominator is all aspects of optimization and risk management, where modeling, simulation, validation and applied mathematics are important tools. Responsible research leader is Professor Erik Dahlquist.

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